EXPERIMENTAL HYPERVELOCITY DUST IMPACT IN OLIVINE: FIB/TEM CHARACTERIZATION OF MICRON-SCALE CRATERS WITH COMPARISON TO NATURAL AND LASER-SIMULATED SMALL-SCALE IMPACT EFFECTS. R. Christoffersen[1], M. J. Loeffler[2], Z. Rahman[1], C. Dukes[3] and the IMPACT Team[4], [1]Jacobs, NASA Johnson Space Center, Mail Code XI3, Houston, TX 77058, USA, roy.christoffersen-1@nasa.gov, [2]NASA GSFC, Greenbelt, MD 20771, USA, [3]University of Virginia, Laboratory of Atomic and Surface Physics, Charlottesville, VA 22904 USA, [4]University of Colorado, Boulder, CO 80309, munsat@colorado.edu.

Introduction: The space weathering of regoliths on airless bodies and the formation of their exospheres is driven to a large extent by hypervelocity impacts from the high relative flux of micron to submicron meteoroids that comprise ~90% of the solar system meteoroid population [1]. Laboratory hypervelocity impact experiments are crucial for quantifying how these small impact events drive space weathering through target shock, melting and vaporization. Simulating these small scale impacts experimentally is challenging because the natural impactors are both very small and many have velocities above the ~8 km s^{-1} limit attainable by conventional chemical/light gas accelerator technology. Electrostatic "dust" accelerators, such as the one recently developed at the Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS) [2], allow the experimental velocity regime to be extended up to 10's of km s^{-1}. Even at these velocities the region of latent target damage created by each impact, in the form of microcraters or pits, is still only about 0.1 to 10 µm in size. Both field-emission analytical scanning electron microscopy (FE-SEM) and advanced field-emission scanning transmission electron microscopy (FE-STEM) are uniquely suited for characterizing the individual dust impact sites in these experiments.

In this study, we have used both techniques, along with focused ion beam (FIB) sample preparation, to characterize the micrometer to nanometer scale effects created by accelerated dust impacts into olivine single crystals. To our knowledge this work presents the first TEM-scale characterization of dust impacts into a key solar system silicate mineral using the CCLDAS facility. Our overarching goal for this work is to establish a basis to compare with our previous results on natural dust-impacted lunar olivine [3] and laser-irradiated olivine [4, 5].

Methods: Single crystals of San Carlos olivine (Fo_{90}) with flat polished surfaces ~1 cm^2 in area were exposed to a stream of Fe metal dust particles in the CCLDAS electrostatic accelerator [2]. As described in [2], a "beam profiler" allows determination of the mass, velocity and axis-relative position of each particle crossing a sensor 1.8 m upstream from the sample. At a particle count rate of ~0.5 particles/sec, we exposed two olivine samples to total counts of 1 x 10^4 (10K) and 4 x 10^4 (40K) particles. Characterization of the 10K sample is reported here and the particle mass-equivalent radius versus velocity distribution for this experiment is shown in Fig. 1.

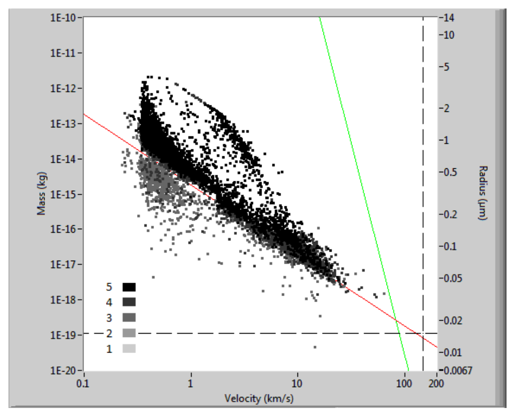

Fig. 1. Fe metal dust particle mass and equivalent radius versus velocity distribution for 10K particle dust impact experiment into San Carlos olivine.

Results: FE-SEM imaging revealed the density of clearly identifiable dust impact features (microcraters) on the 10K sample to be ~6300 cm^{-2}. Although the microcrater size distribution remains to be precisely determined, the microcraters ranged between 0.1 to 5 µm in diameter (Fig. 2). The microcraters have ovoid to sub-circular shapes, with irregular/serrated rims due to spallation fracturing (Fig. 2). FE-SEM reveals varying distributions of splat and droplet-shaped grains of metallic Fe lining crater cavities, which are interpreted to be from shock-melting of the impacting Fe metal dust grain.

A FIB cross-section of the Fig. 2b microcrater was prepared for imaging and nanoscale EDX analysis using the JEOL 2500SE analytical FE-STEM at NASA JSC (Fig. 3). Other than the areas of shock melted Fe-metal impactor on the crater walls, little

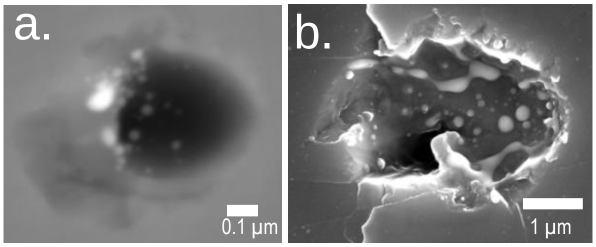

Fig. 2. SEM images of sub-micron (a) and micron (b) size Fe metal dust impact microcraters.

additional shock-melted material was observed with the exception of a single 200 nm bleb of olivine-composition glass along one area of the crater wall. More notable is the formation of a complex shock deformation zone extending 1-2 µm into the olivine from the crater cavity. The zone is characterized by: 1) areas with exceedingly high dislocation density, some with linear, sub-grain-like geometries, 2) geometrically regular fracture networks in which the nm-scale length, spacing and displacement of the fractures results in mosaicism and/or complete asterism in electron diffraction patterns, 3) longer, more widely-spaced linear fractures likely corresponding to those visible in SEM images, and 4) areas of nanocrystalline olivine just below the crater floor.

Discussion: The intrinsic spread in the velocity and size distributions of the experimental dust particles limits our knowledge of the exact size and velocity of the impactor that formed any one microcrater. This limitation can and will be countered in future experiments by instrumental velocity filtering. For now, we can nevertheless report that for one of the largest microcraters produced in our experiments we find little or no evidence of shock melting (or vaporization) but a high degree of solid-state shock deformation in the olivine target. Preliminary SEM observations of other microcraters on the sample also do not appear to show significant olivine-derived shock melt. This is in marked contrast to our FE-STEM observations of a slightly larger (~10 µm) microcrater in a natural lunar olivine [3] that showed a uniform 1-2 µm wide lining of shock-melted olivine around the crater cavity. Also, the small amount of olivine shock melt identified in our sample did not contain nanophase Fe metal ($npFe^0$), whereas $npFe^0$ was abundant in the lunar olivine shock melt [3]. Although the size and velocity of the impactor for the natural crater in [3] cannot be known precisely, velocity filtering in future CCLDAS experiments will allow us to know this with fair precision for indiv-

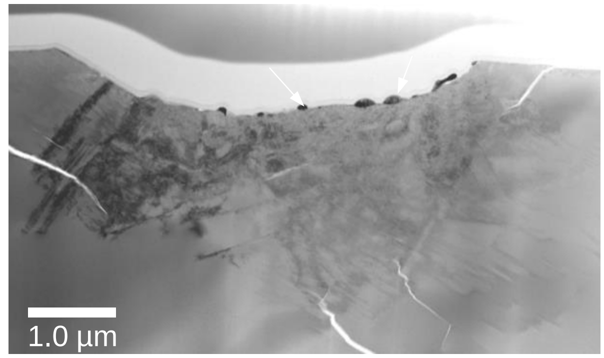

Fig. 3. Bright-field STEM image of FIB-sectioned dust impact microcrater in San Carlos olivine. Arrows show shock melted Fe metal dust impactor.

-idual experimental microcraters. This will allow development of a more quantitative shock effects calibration for impacts of this size. Relative to the effects we have observed by FE-STEM in scanned and stationary spot pulsed laser irradiation of olivine [4, 5], the dust impacts show dramatically less melt/vapor deposition but a much higher degree of shock deformation. One possibility for the difference in amount of melt/vapor deposit formed between the two experiments may be that as an energy-deposition analog, the laser pulse scales to impacts from the highest (>>10 km s^{-1}) velocity meteoroids, whereas the dust microcraters we have so far studied may only be from lower velocity (≤1 km s^{-1}) impacts. Although significant shock deformation is not necessarily expected in laser irradiation, our current findings are an important reminder that lasers fall short as an analog to physical impacts in this respect. The “laser-as-proxy-for-impact” assumption will be tested further once we obtain improved data for the impactor size and velocity corresonding to individual microcraters in future dust impact experiments.

References: [1] Grun E., Horanyi M., and Sternovsky Z. (2011) *Planet. Space Sci.* 59, 1672-1680. [2] Munsat T. et al (2013) *44th LPSC*, abstract # 2585. [3] Noble S. K. et al. (2016) *47th LPSC*, abstract # 1465. [4] Christoffersen R. et al. (2016) *47th LPSC*, abstract # 2747. [5] Loeffler M. J. et al. (2016) *MAPS* 51(2), 261-275.